



Magnesium Technology and Manufacturing for Ultra Lightweight Armored Ground Vehicles

**by Kyu Cho, Tomoko Sano, Kevin Doherty, Chian Yen, George Gazonas,
Jonathan Montgomery, Paul Moy, Bruce Davis, and Rick DeLorme**

ARL-RP-236

February 2009

*A reprint from the Proceedings of the 2008 Army Science Conference,
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Aberdeen Proving Ground, MD 21005-5069

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REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE (DD-MM-YYYY) February 2009		2. REPORT TYPE Reprint		3. DATES COVERED (From - To) 21 September 2007–20 September 2008	
4. TITLE AND SUBTITLE Magnesium Technology and Manufacturing for Ultra Lightweight Armored Ground Vehicles				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Kyu Cho, Tomoko Sano, Kevin Doherty, Chian Yen, George Gazonas, Jonathan Montgomery, Paul Moy, Bruce Davis,* and Rick DeLorme*				5d. PROJECT NUMBER W911NF-07-2-0073	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory ATTN: AMSRD-ARL-WM-MD Aberdeen Proving Ground, MD 21005-5069				8. PERFORMING ORGANIZATION REPORT NUMBER ARL-RP-236	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES *Magnesium Elektron North America, Inc., 1001 College St., Madison, IL 62060 A reprint from the <i>Proceedings of the 2008 Army Science Conference</i> , Orlando, FL, 3 December 2008.					
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15. SUBJECT TERMS magnesium, high strength, armor					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UL	18. NUMBER OF PAGES 14	19a. NAME OF RESPONSIBLE PERSON Kyu Cho
a. REPORT UNCLASSIFIED	b. ABSTRACT UNCLASSIFIED	c. THIS PAGE UNCLASSIFIED			19b. TELEPHONE NUMBER (Include area code) 410-306-0820

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ABSTRACT

The current paper summarizes magnesium alloy metallurgy and wrought manufacturing with an initial emphasis on the Elektron WE43 alloy system for lightweight armored ground vehicle applications. Engineering design factors are reviewed and initial mechanical property data are presented along with ballistic results and findings from blast simulations. Finally the future role of magnesium alloys in ultra light metallic armor is discussed in terms of material development and application.

1. INTRODUCTION

Magnesium (Mg) is the lightest structural and engineering metal at a density of 1.74 g/cm^3 that is approximately 1/5, 2/5, and 2/3 the weight of iron, titanium, and aluminum, respectively (Emley, 1966; Avedesian and Baker, Ed., 1999). Figure 1 graphically summarizes the normalized density of Mg alloys and compares it with those of AA5083, 4340 steel and Ti-6V-4Al alloy.

Mg alloys are being considered as extremely attractive lightweight materials for a wide range of the Army's future applications where weight reduction is a critical requirement because of its low density. Furthermore, magnesium has good vibration damping capacity (Sugimoto et al., 1997) and low acoustic impedance characteristics (Martin et al., 2006) that could be of additional benefit to vehicle applications. Ma et al. (2008) have highlighted the importance of Mg alloy research. The report set out near- and long- term property goals of ~350 MPa (high strength) and ~500 MPa (ultra high strength) in yield strength, with a failure strain (ductility) of 0.1, in order to promote widespread Mg usage.

It is necessary to emphasize that these technologies must be scalable to commercial production volumes in order for the application of magnesium alloys to be realized in lightweight armored ground vehicle applications. In order to address wrought Mg alloy

manufacturing capacity, the U.S. Army Research Laboratory (ARL) and Magnesium Elektron North America, Inc. (MENA) have formed a multiyear Cooperative Agreement (CA) to collaboratively develop and establish commercial scale direct chill (DC) cast Mg alloy slab capacity, and related downstream thermomechanical processing for wrought Mg alloy armor plate fabrications. Two Mg alloys being developed under the CA are high strength Elektron WE43 (Magnesium Elektron, Datasheet 478) and ultra high strength Elektron 675 (Magnesium Elektron, Datasheet 102).

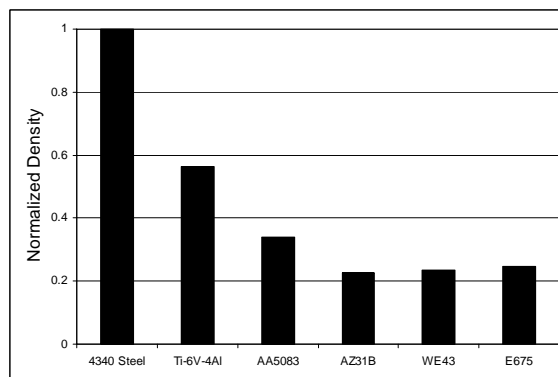


Figure 1. Normalized densities comparison of magnesium alloys with 4340 steel and titanium alloy.

Both Elektron WE43 and Elektron 675 are yttrium, rare earth and zirconium based alloy systems. The rare earths are from the Lanthanides group in the periodic table of elements. These additions impart solid state solution strengthening and precipitation hardening of the alloy systems, which are both heat treatable.

Elektron WE43 is conventionally used in sand castings for the fabrication of applications such as helicopter gearboxes and auto-sport equipment. The cast alloy is relatively high strength when compared to other magnesium alloys, has good elevated temperature properties up to 200°C, good creep performance and flammability resistance (Yates and Lyon, 1992). Elektron 675 is a developmental alloy with exceptionally high

mechanical properties at room and elevated temperatures (200°C).

Ancillary process and material models are planned to aid the DC casting manufacturing scale-up and related secondary thermomechanical process optimization in order to optimize material properties and deformation characteristics with respect to structural and survivability requirements of the systems of interest.

The current paper summarizes generalized Mg alloy metallurgy, deformation mechanisms, and wrought manufacturing scheme with an initial emphasis on the Elektron WE43 alloy system for lightweight armored ground vehicle applications. Particular attention is given to corrosion protection, flammability resistance, and joining characteristics. Initial mechanical property findings are reviewed and these have been used to conduct simulations to quantify the potential effectiveness against various hypothetical dynamic and penetration impact conditions. The simulation results on protection effectiveness have been compared with similar data from other traditional metallic materials in order to identify the advantages of the developed Mg alloys.

2. MAGNESIUM METALLURGY, CORROSION BEHAVIOR, JOINING and FLAMMABILITY

2.1 Metallurgy

Mg physical metallurgy is strongly governed by the hexagonal close packed (HCP) structure ($c/a = 1.624$) and Mg atomic size ($a = 0.320$ nm). Mg atomic size favors the solid solubility of a wide range of solute elements. Although the physical properties of Mg alloys are solely affected by the amount of each alloying constituent, process optimization affects the resulting Mg alloy properties. Therefore, understanding of the process and property relationship in a particular alloying system is one of the most important factors in designing the high performance Mg alloy and optimizing the alloy system.

2.2 Deformation Mechanisms

Mg alloys have an inherent formability deficiency due to the limited number of dislocation slip systems available in the HCP crystal structure (Avedesian and Baker, 1999). At ambient temperature and low strains, primary dislocation slip occurs on the (0001) basal plane and in the $\langle 11\bar{2}0 \rangle$ close packed direction; secondary dislocation slip occurs on the prismatic $\{10\bar{1}0\}$ planes

and in the $\langle 11\bar{2}0 \rangle$ direction, see Figure 2. At higher strains, deformation is accommodated by the formation of twins. This is due to the low symmetry and lack of available slip systems in magnesium's HCP structure (Humphreys and Hatherly, 2004). This is true at low

deformation temperatures and is why magnesium is difficult to form at room temperature. At elevated temperature, thermally activated dislocation slip occurs on pyramidal $\{10\bar{1}1\}$ slip planes in the $\langle 11\bar{2}0 \rangle$ direction. This is why magnesium alloys are commonly worked at temperatures greater than 200°C (Dow, 1982).

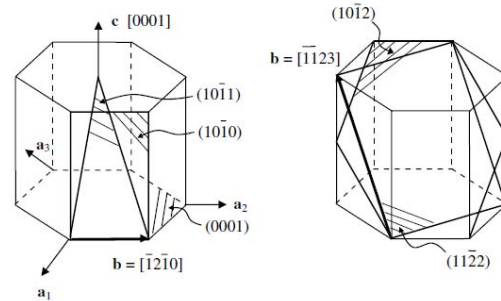


Figure 2. Hexagonal close packed planes and directions relevant to slip of dislocations in magnesium alloys (Agnew and Duygulu, 2005)

2.3 Corrosion Behavior

Several factors that heavily influence the corrosion performance of Mg alloys (Godard et al., 1967) are alloy chemistry, fabrication method, surface coatings, service environment and application design. Since Mg alloys are anodic to almost all metals and alloys, galvanic corrosion is a potential problem in presence of electrolytes (Avedesian and Baker, Ed. 1999). The effect of various alloying elements on the corrosion resistance of Mg is shown in Figure 3 (Hanawalt et al., 1942). Al, Mn, Sn, Pb, Si, Na, Th, Zr, Be, Ce, Pr, and Y are known to have negligible effects on the corrosion performance when present in concentrations exceeding their solubility limits, up to a maximum of 5 wt%. Ag, Cd, Ca, and Zn have moderate accelerating effects on corrosion rates. However, Fe, Ni, Co and Cu have extremely harmful effects because of their low solubility limits in Mg and their ability to serve as active cathodic sites, which promotes galvanic corrosion on a microstructural scale.

Figure 4 shows the relative corrosion rates of various Al alloys and Mg alloys. It can be seen that Elektron WE43 is only marginally above the Al casting alloys A201-A206. Figure 5 shows the improved corrosion resistance of Elektron WE43 relative to the older alloy ZE41. The images show exfoliation of the surface coating, resulting from a scored line in the protective layer, which was then exposed to a standard salt fog test. The Elektron WE43 exhibited no delamination.

In addition to general corrosion of the base material, careful consideration must be given to the design of the application to maximize corrosion protection via optimized coating systems and minimization of

environmental factors i.e. eliminating water traps in the design. Furthermore, assembly methods need to be designed that prevent galvanic corrosion as a result of intimate contact of dissimilar metals.

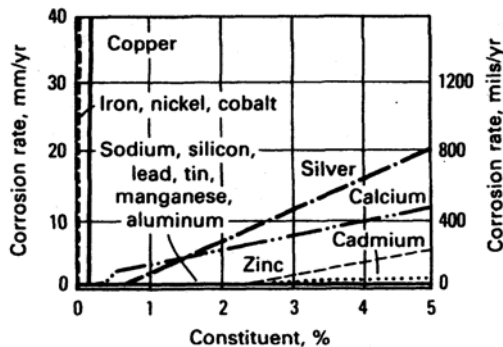


Figure 3. Effect of alloying and impurity metals on the corrosion rate of magnesium in 3% NaCl solution. (Hanawalt et al., 1942).

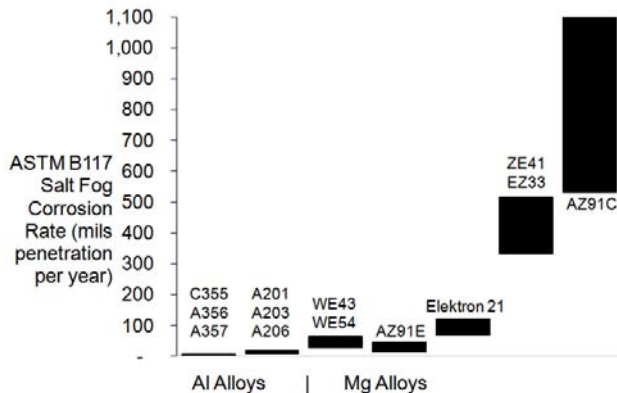


Figure 4. ASTM B117 Salt Fog corrosion rates, corrosion penetration depth in 10^{-3} inch, of selected Al and Mg alloys.



Figure 5. Proper alloy selection and adequate engineering solutions could potentially mitigate Mg alloys corrosion. Photograph depicting the improved corrosion resistance of Elektron WE43 vs. ZE41.

FMC has used magnesium castings for M113 components such as fans, gearboxes, differential housings, and floor plates. The big problem for the M113

in the Vietnam era was corrosion as cited by FMC (Liu, 2000). However, Clow (1993) reported that significant improvement has been made in corrosion resistance of cast magnesium alloys: "This improved corrosion resistance and coating techniques combined with the metal's light weight, castability and ease of machining has lead to rapid growth in automotive applications in recent years." He also reported the results of the usage of uncoated die-cast clutch magnesium housings in vehicles operated in Nova Scotia, which was selected for its severe climate and heavy usage of de-icing salt. In 1988, after 5 years of service, forty-one of these were inspected. All were found to be in good serviceable condition. This small case study shows that with the correct design criteria corrosion of Mg components need not be an issue even in the harshest of environments.

2.4 Joining

Magnesium can be joined using welding, mechanical fasteners such as rivets, and adhesive bonding. For armor vehicles welding is the only method that will instill enough strength. Magnesium is weldable by arc, resistance, and friction stir welding processes. The physical properties of magnesium make welding it akin to the processes used for aluminum (Klain, 1957). In magnesium-aluminum-zinc alloys, such as AZ31B, aluminum content can aid weldability by helping to refine the grain structure.

Gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW) are the two most common processes for welding magnesium. These processes are used for repair welding and removal of defects in Elektron WE43 sand castings. Friction stir welding is a solid state joining technique that has processing advantages over fusion welding. It facilitates sound joints with little porosity, good mechanical properties, and minimal distortion (Esparza et al., 2002). This method of welding has been successfully demonstrated in a number of Mg alloys.

2.5 Flammability

There are often misconceptions regarding the flammability of magnesium and its alloys. In a finely divided state such as powders, ribbon, machined chips or swarf it is necessary to take precautions such as storage in lidded steel drums, away from moisture. However in solid form magnesium is very difficult to ignite. The material has a relatively high thermal conduction and as such the solid metal dissipates any localized heat. Furthermore for ignition to occur the material must exceed its solidus temperature. For Elektron WE43 this is in excess of 535°C.

A benefit of Elektron WE43 and Elektron 675 is that their high yttrium content leads to a thick, yttrium rich,

oxide skin forming over any molten alloy (Blandin et al., 2004). This acts to prevent ignition and results in Elektron WE43 self extinguishing, even in the event of ignition.

Sustained major fires are generally the cause of magnesium alloy ignition, as is the case with other non-ferrous metals such as aluminum. Thompson (Liu, 2000) cited an incident involving a helicopter engine fire with magnesium alloy transmission housing. In that incident, he observed that it was the sustained major fuel fire that eventually caused the magnesium alloy housing to ignite, however this did not add any further damage following the fuel fire. For a weapon system, the effects of propellant fires need to be examined.

It appears that the only possible hazard is damage due to magnesium ignition resulting from a sustained fuel fire, during which such extensive damage is done by the time the magnesium ignites there is little cause for concern.

3. WROUGHT ELEKTRON WE43 ALLOY FABRICATION AND PRELIMINARY PROPERTIES

The ASTM designation of Elektron WE43 Mg alloy is WE43A. Its nominal chemical composition (Magnesium Elektron: Datasheet 478) is summarized in Table I. Currently wrought Elektron WE43 alloy is commercially available in extruded or forged parts. Vendor published physical properties are summarized in the Table II (Magnesium Elektron, Datasheet 441; Magnesium Elektron, Datasheet 478). Note that Elektron WE43 is typically heat treated to -T6, solutionized and artificially aged; or -T5, artificially aged, condition.

Table I. Elektron WE43 Chemical Composition

Element	Y	RE*	Zr	Mg
Wt %	3.7 – 4.3	2.4 - 4.4	0.4 min	balance

*Rare earth elements consists of 2.0 – 2.5 % Nd and 0.4 – 1.9 % of Yb, Er, Dy, Gd, and other rare earth elements.

Table II. Physical Properties of Elektron WE43 Mg Alloy

Density (g/cm ³)	CTE (10 ⁻⁶ /K)	TC (W/mK)	ER (nΩm)	SH (J/kgK)
1.84	26.7	51	148	966

CTE: coefficient of thermal expansion; TC: thermal conductivity; ER: electrical resistivity; SH: specific heat

The production route of magnesium plate is shown schematically in Figure 6. The process involves DC casting a slab. This is initially stress relieve annealed to alleviate any residual stresses generated during casting that might cause the slab to crack. This is then scalped to produce a machined surface for rolling. The slab is preheated and rolled hot to finish gage. The plates are

then given a -T5 heat treatment to optimize the mechanical properties and cut to size for the customer.

3.1 Fabrication

Magnesium Elektron North America currently has a capacity in excess of 10,000 tons per annum of magnesium plate produced via this route.



Figure 6. A schematic of the Elektron WE43 production process route.

3.2 Mechanical Properties

The relationship between plate and sheet gages and mechanical properties is shown in Figure 7. It can be seen that there is a significant increase in the yield strength (YS) and ultimate tensile stress (UTS) as the gage becomes thinner. Conversely the elongation of the material decreases with reduced gage. The current challenge is to obtain the high strength found in thin sheet, with a higher elongation, in plate. This is being addressed via the modification of the production route, optimization of the -T5 heat treatment and increasing the strength of the base alloy by utilizing Elektron 675.

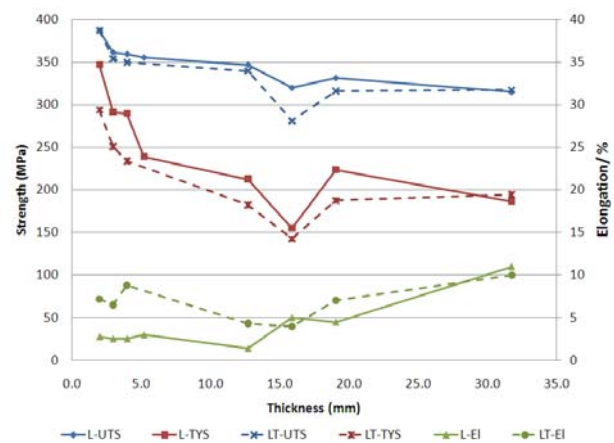


Figure 7. Graph showing the relation between gage and tensile properties of preliminary Elektron WE43-T5.

Table III. Tensile Properties of Elektron WE43 Rolled 4mm sheet comparing as rolled -F temper with two heat treated -T5 tempers.

Temper	Orienta tion	UTS (MPa)	Failure Strain (%)	Yield Strength (MPa)
F	L	302	9.4	223
	LT	291	20.0	195
T5	L	351	4.2	287
	LT	343	8.6	225
T53	L	305	9.3	252
	LT	297	23.5	235

The resulting preliminary mechanical properties from as rolled (-F) and 2 different -T5 heat treatments are shown in Table III. The aim of the -T53 was to overage the material in order to regain some of the elongation that was lost during the normal -T5 treatment, whilst maintaining strength. It can be seen that the -T5 material had higher UTS and YS relative to the -F condition, however the elongation dropped dramatically. The -T53 heat treatment did restore the elongation and improved it relative to the -F temper, however at the loss of mechanical strength. Further work is required to optimize this process.

3.3 Microstructure

Scanning electron microscopy reveals that Elektron WE43 wrought plate has an equiaxed microstructure interspersed with yttrium and rare earth second phase particles. The grain size of the material can be seen to be 50-70 μ m, from Figure 8. The microstructure shown in Figure 8 appears fully recrystallized. Some twinning is present; however, the majority of this is thought to be residual damage from the sample preparation.

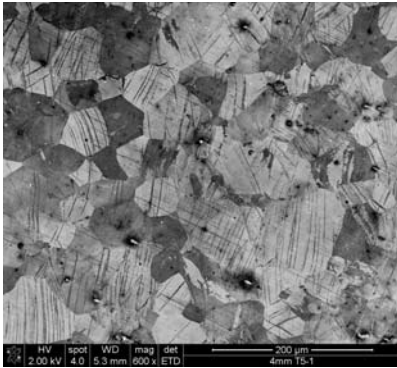


Figure 8. Scanning electron micrograph of Elektron WE43 microstructure.

4. Ballistic Properties and Blast Simulation

4.1 Ballistic Properties

The common magnesium plate alloy AZ31B-H24 was recently evaluated by Jones et al. (2008). The threats used in that study were .30 cal M2 AP, .50 cal M2 AP, and the .50 cal and 20 mm Fragment-Simulating Projectiles (FSPs). All threats were at zero degrees obliquity, i.e., normal to the plate. This alloy shows similar performance against the AP threats as aluminum alloy 5083-H131 (MIL-DTL-46027K) on an areal density basis. That is, the plate will be thicker, but it will weigh about the same and have the same amount of performance against AP threats. Aluminum alloy 5083-H131 showed slightly better performance than AZ31B-H24 against the FSP threats. Metallurgical reasons for its performance are being investigated.

Similar tests were performed on preliminary Elektron WE43 plate using .30 M2 AP and .50 FSP. These demonstrated the superior ballistic performance of Elektron WE43 over both AZ31B-H24 and MIL-DTL-46027K acceptance values on an areal density basis, see Figures 9 and 10.

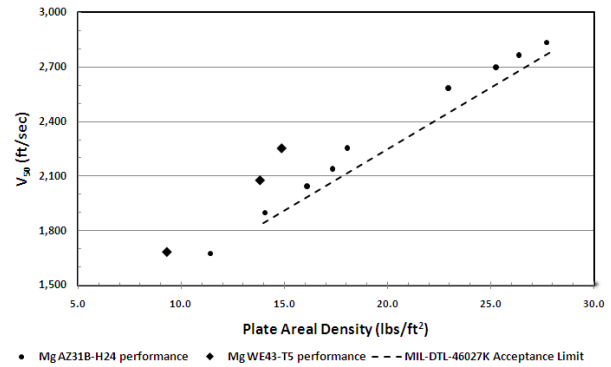


Figure 9. Ballistic performance of Elektron AZ31B-H24 and Elektron WE43-T5. Threat: .30 cal M2 AP

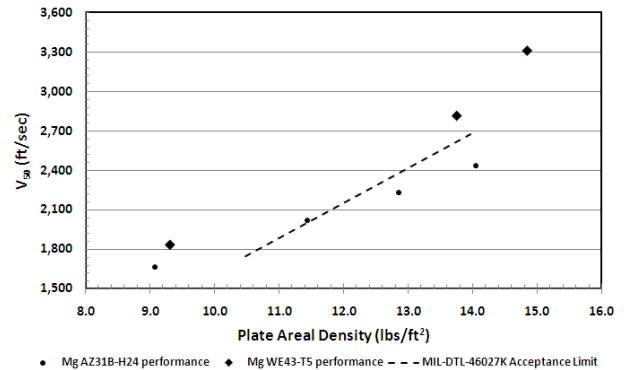


Figure 10. Ballistic performance of Elektron AZ31B-H24 and Elektron WE43- Threat: .50 cal FSP

Magnesium alloys show true promise as an armor alloy due to their plate stiffness. Its reduced modulus is countered by its low density, which allows very high plate stiffness on an equal weight basis. This is demonstrated by the values in Table IV showing calculated Belleville spring constants for a variety of metals using equal areal density. The increased second moment of inertia of thicker plates contributed to the increased stiffness. Ghiorse et al. (2002) showed that backing plate stiffness is an important parameter for ceramic-based structural armor. If an alloy can be designed with improved break-out performance, then it should be able to favorably compete with polymer matrix composites on a weight and space basis.

4.2 Ballistic Simulations

The impact and penetration response of AZ31B-O alloy by a high-velocity mild-steel fragment (30 HRC)

using AUTODYN (Autodyn Theory Manual, 2004) 2-D axisymmetric analysis of the FSP is presented. The results of the simulation for the .50 cal FSP perforation of a 11.38 pounds per square foot (psf) AZ31B-O target are illustrated in Figure 11 and are corroborated by the experimentally determined V_{50} impact velocity of 639 m/s reported by Jones et al. (2008); this is on the order of the ballistic limit effectiveness of equal areal density targets consisting of RHA steel material. The simulation and ballistic limit results indicate that magnesium alloy materials may have the potential for improvement in the degree of protection offered against FSPs (for the same weight of armor); although we have a limited knowledge of the dynamic failure mechanisms active in the magnesium alloy materials.

Table IV. Belleville Spring Constants calculated for plates of different metals and equal areal densities.

Metal	Plate Thickness, in	Plate Stiffness, E6 lb/in
RHA (Steel Armor)	0.245	0.08
Ti-6Al-4V	0.434	0.28
7075-T6	0.702	0.75
A356-30SiC (MMC)	0.702	4.70
2195-T8	0.712	0.83
5059-H131	0.728	0.84
AZ31B-H24	1.085	1.78

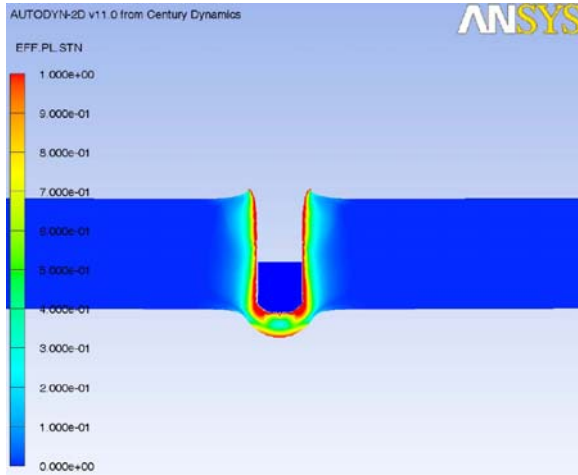


Figure 11. V_{50} ballistic perforation of a 11.4 psf AZ31B-O target by a .50 cal FSP impacting at 639 m/s.

4.3 Blast Simulations

ARL has been using a dynamic simulation approach to conduct parametric studies for screening potential materials for blast protection. Two key material properties have been identified that dominate the blast protection capacity: the yield strength and failure strain (ductility).

The blast protection efficiency of Elektron WE43 was evaluated by performing dynamic simulation of a panel subjected to blast testing using the Vertical Impulse

Measurement Facility (VIMF) at ARL. Figure 12 shows a half FE model of the VIMF test setup. The 4 ft x 4 ft x 2.93 in test panel was subjected to a mine-blast from below. Note that the panel thickness was determined by the area density equivalent to a 2 in aluminum alloy. Using an LS-DYNA simulation, the maximum panel deflection at the panel center was determined by computing the dynamic deformation of the panel. The maximum deflection was then used to rank the blast protection efficiency of a particular material, i.e. the less deflection the better.

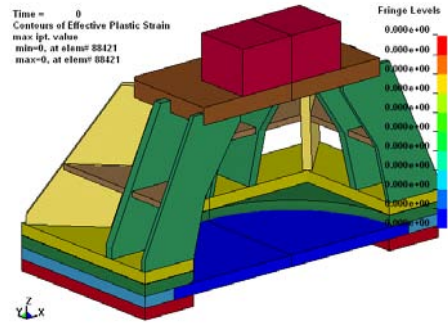


Figure 12. FE model for VIMF blast test simulation

Figure 13. compares the maximum vertical deflections of Elektron WE43-F and Elektron WE43-T5 with the deflections of AA5083-H131 and AA2195-AU2. Figure 13 also shows the maximum effective plastic strain predicted in the panels.

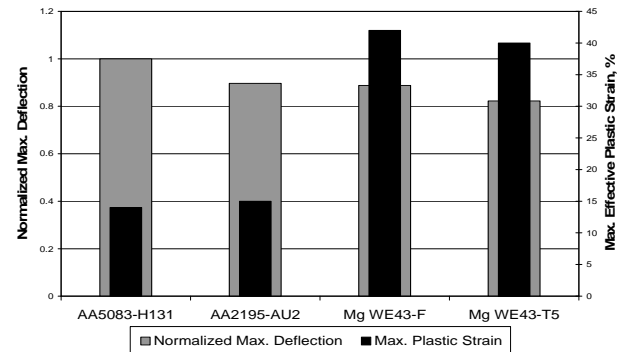


Figure 13. Comparison of predicted maximum panel deflection and maximum effective plastic strain of AA5083-h131, AA2195-AU2, Elektron WE43-F and Elektron WE43-T5

It is important to note that the actual material failure strain must be greater than the computed maximum plastic strain to prevent the failure of the panel. Figure 13 shows that the deflection capacity of Elektron WE43 is compatible with the aluminum alloys. However, it requires that Elektron WE43 have an elongation failure strain of more than 43% to maintain its protection efficiency by preventing panel failure.

5. Material Selection Criteria

In general, strengths of typical Mg alloys are comparable to those of other metals, as graphically represented in Figure 14A. On a specific basis, both strength and stiffness of Mg alloys are very comparable to those of other popular structural metals, as seen in Figure 14B. The specific mechanical properties of Mg alloys are expected to improve as a result of new high (Elektron WE43) and ultra high (Elektron 675) strength Mg alloys that are currently being developed. Figure 15 summarizes quasi-static specific mechanical properties and failure strain (i.e., ductility) of three Mg wrought alloys (AZ31B, WE43, and E675) and compares them with those of 4340 steel and Ti-6V-4Al alloy benchmarks. The specific properties of Mg alloys have gained tremendous attention in recent years and are one of many synergetic factors that drive Mg utilization for vehicle survivability related applications.

The density and elastic modulus are two intrinsic material properties that are strongly affected by the rule of mixtures in constituent elemental chemistries and constituent phases. These intrinsic properties are very difficult to tailor using conventional metallurgy. On the other hand, strength and strain to failure (e.g., ductility) are two well known extrinsic material properties that are very strongly influenced by alloying, microstructure manipulation, and deformation conditions. Therefore, the Mg alloy optimization route will deal with improving extrinsic properties. Most metals including Mg alloys, however, exhibit very strong inverse proportionalities in strength and ductility. That is, any gain in strength resultant from alloying, microstructure modifications, and/or changes in deformation behaviors and conditions, occurs at the expense of ductility. Recent research focuses on improving both strength and ductility of Mg alloys using hybrid concepts in classical metallurgy and nano microstructure manipulations.

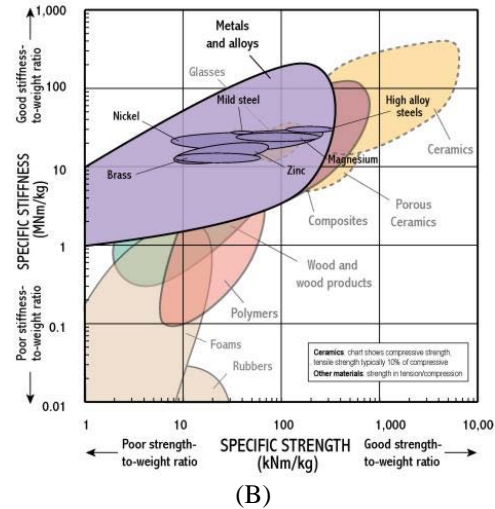
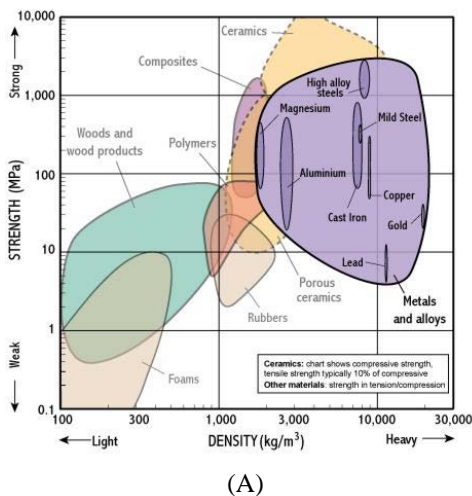


Figure 14. Materials' property comparison graphs (A) Quasi-static strength as a function of density. (B) Specific stiffness versus specific strength (University of Cambridge: 2002).

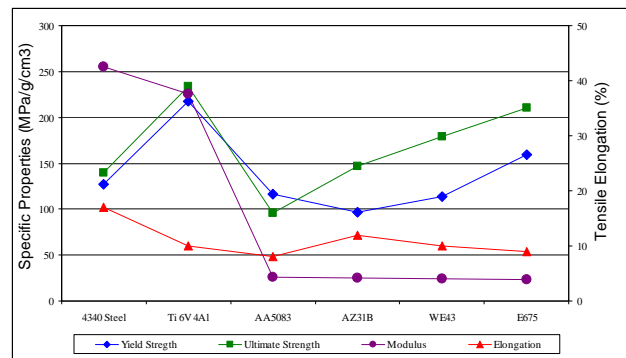


Figure 15. Specific properties and elongation comparison of Mg alloys, 4340 steel, and Ti-6V-4Al alloy.

From a metallurgical perspective, it is of utmost importance to improve and balance appropriate extrinsic materials properties, such as yield strength and ductility, under a wide range of strains and strain rates by manipulating the microstructures to change the yield criteria and the deformation conditions. The ultimate metallurgical goal in Mg alloy optimization is to simultaneously elevate both strength and ductility (Ma, 2006) of Mg alloys with appropriate strain rate sensitivities using the aforementioned microstructural artifacts.

Stiffness considerations are also equally important in survivability related structures. A gain in stiffness (e.g., elastic modulus) is typically engineered through a compositing concept such as metal matrix composites (MMC) (Lloyd, 1994) and multi-scale nano-micro composites (Ye et al., 2005). For a combat ground vehicle survivability application, a multi-layered material concept is widely anticipated where each material layer addresses a specialized function to maximize the overall

system survivability performance. It is felt that the new high strength magnesium plate alloys, currently under development in this program of work will play a significant role in composite armor solutions in future armor applications.

6. CONCLUSIONS

The early results from the development of high strength magnesium armor materials have shown significant promise for the material in its ability to become part, if not a whole, of an ultra light weight armor solution for future military applications. However, the early results indicate a need to improve the ductility of the materials without the loss of mechanical strength. Furthermore the application of the new magnesium alloy systems will require a knowledge base to be established amongst engineers containing the specific design requirements to join the materials and reduce the risk of corrosion. The U.S. Army Research Laboratory and Magnesium Elektron North America continue to work in close partnership to find solutions to these issues and generate the required manufacturing and fabrication knowledge base to make ultra lightweight metallic armor a future reality.

7. ACKNOWLEDGEMENTS

The authors gratefully acknowledge the contributions and support of James Catalano of U.S. Army Research Laboratory in metallographic sample preparations.

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